Leptobigenesis: A unified origin of matter and dark matter

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Dark Matter

1. The existence of Dark matter is well established;
2. The relic density of Dark matter is known with precision;
   - Ordinary matter $\Omega_b h^2 = 0.0223 \pm 0.0007$,
   - Dark matter $\Omega_{DM} h^2 = 0.106 \pm 0.008$,
   - Dark energy dominates;
3. Basis properties: Neutral, Massive, Non-Baryonic, Weakly interacting, Stable
4. The identity of Dark matter is still a mystery.

No candidate in standard model of particle physics: Go Beyond SM ;

Popular candiates: weakly interacting massive particles (WIMPs), stability with Z_2 symmetry

- the lightest Supersymmetric particle (LSP): Neutralino, Gravitino, Sneutrino, Axino, ... ;
- Lightest Kaluza-Klein particle (LKP);
- the lightest T-parity odd particle in LHT;
- ... ;

WIMPs: thermal relics

The origin of the WIMPs abundance:

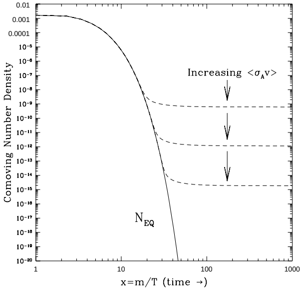
- stable particle pair annihilation:

$$\chi\bar{\chi} \to f_{SM}\bar{f}_{SM}$$

- relic density:

$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27}\mathrm{cm}^3/\mathrm{sec}}{\langle \sigma v \rangle}$$

$$\Omega_\chi h^2 \sim 0.11 \;\; \text{for} \;\; \sigma \sim 1\text{pb}$$



- WIMP "miracle"

$$\sigma \sim \frac{g^4}{M_{weak}^2} \sim 1\text{pb}$$

Baryon Asymmetry in the Universe

1. CMB and Nucleosynthesis

$$Y_b \equiv \frac{n_b - n_{\bar{b}}}{s} = \frac{n_b}{s} \sim 10^{-10}$$

2. Sakharov conditions for Baryogenesis:
    - Baryon number is violated;
    - C and CP are violated;
    - Departure from thermal equilibrium;

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   - Baryon number is violated;
   - C and CP are violated;
   - Departure from thermal equilibrium;
3. The SM fails: too small CKM CP violation and no strongly electroweak phase transition

- Solar and atmospheric neutrino oscillations $\Rightarrow$ massive ν's ;
- In the minimal SM $m_\nu = 0$;

"Seesaw" and Leptogenesis

- Solar and atmospheric neutrino oscillations $\Rightarrow$ massive ν's ;
- In the minimal SM $m_\nu = 0$;
- Add three SM singlets N: $\mathcal{L} = y\bar{L}HN + M_R NN$;
- the Seesaw mechanism:

$$m_\nu \sim -\frac{y^2 v^2}{M_R}$$

“Seesaw” and Leptogenesis

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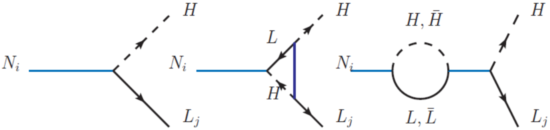
- lepton number violated, new CP violation source and the heavy neutrinos decay out of equilibrium: Leptogenesis - an elegant way to generate BAU ;

Leptogenesis



- Direct CP violation at one-loop level.
- lepton asymmetry:

$$\epsilon \equiv \frac{\sum_\alpha \left(\Gamma(N_1 \to HL_\alpha) - \Gamma(N_1 \to \bar{H}\bar{L}_\alpha)\right)}{\sum_\alpha \left(\Gamma(N_1 \to HL_\alpha) + \Gamma(N_1 \to \bar{H}\bar{L}_\alpha)\right)}$$

- Baryon asymmetry with sphaleron processes:

$$\eta_b \equiv \frac{n_B}{n_\gamma} \simeq -\frac{3}{4} \cdot \frac{g_{*s}^0}{g_{*s}} \cdot \frac{28}{79} \cdot \kappa \cdot \epsilon \,,$$

where g_{*s}^0 and g_{*s} are the total number of relativistic degrees of freedom today and during sphaleron, κ is the washout factor.

Can the baryon and Dark matter abundance have the same origin?

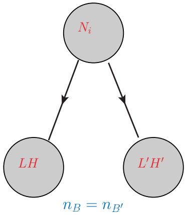
Leptobigenesis

- One mirror sector is added, sharing a common set of three Majorana neutrinos N_i with the SM.
- The coulpings are same due to the mirror symmetry. Leptogenesis leads

$$n_B = n_{B'} \Rightarrow m_{DM} = \frac{\Omega_{DM}}{\Omega_b} m_N$$

Light Dark matter ($m_{DM} \sim 5$ GeV)

- In order to get large mirror Higgs fields VEV, soft breaking terms are included.



Asymmetric Dark matter

- DM density arises from DM matter-antimatter asymmetry;
- Assign a hidden global charge Q and generate the asymmetry through out-of-equilibrium interactions, the lightest asymptotic states are DM;
- The fact $\Omega_{dm} \sim \Omega_{baryon}$;
- Assume there is conservation for SM global number q and hidden charge Q,

$$qn_{b-\bar{b}} = -Qn_{dm-\bar{dm}}$$

then the masses are related;

ADM Models:

TechBaryons (S.Nussinov PLB165(1985)55);
D.B.kaplan PRL68(1992)741;
Mirror DM (R. Foot, PRD52(1995)6595),
Mirror DM (Berezhiani PRD52(1995)6607);
ADM (PRD79(2009)115016), ...

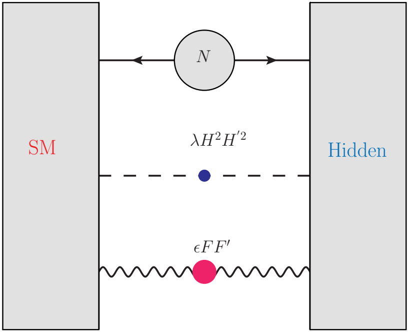
The complete model

- Two Higgs doublet in both sectors: $H_{u,d}, H'_{u,d}$
  - taking a relatively large $\tan\beta' \equiv v'_u/v'_d$, $m_{d'}$ could be smaller than $m_{u'}$, in which case the mirror neutron is the lightest mirror baryon ;
  - Non-vanishing VEVs of charged components of mirror doublet Higgs break the $U(1)_{Q'}$ and lead a massive $\mathcal{O}(100\mathrm{MeV})$ mirror photon ;
- One Triplet Higgs is added to each sector. Neutrino mass matrix:

$$\mathcal{M} = \begin{pmatrix} \mu & M_D & 0 \\ M_D^T & M_R & M_D'^T \\ 0 & M_D' & \mu' \end{pmatrix}$$

- A kinetic mixing between mirror photon and photon $(\epsilon_\gamma F^{\mu\nu} F'_{\mu\nu}/2)$ is also included, which makes the mirror photon to be the messenger.

The portals



Search for a dark massive photon

(A New Proposal to Jefferson Lab PAC35)

Search for a New Vector Boson A' Decaying to e^+e^-

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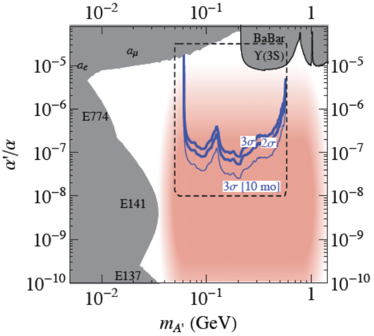


The mirror nucleons

The mirror nucleon masses:

$$
\begin{aligned}
m_{p'} &= k_{p'}\Lambda'_{QCD} + 2h^{p}_{u'}m_{u'} + h^{p}_{d'}m_{d'} \\
m_{n'} &= k_{n'}\Lambda'_{QCD} + 2h^{n}_{d'}m_{d'} + h^{n}_{u'}m_{u'}
\end{aligned}
$$

Λ'_{QCD} grows slowly with the increasing of v'_{wk}, $m_{n',p'}$ are mainly dominated by the quarks masses.

$$
\begin{aligned}
m_{p'} &= 2m_{u'} + m_{d'} \\
m_{n'} &= 2m_{d'} + m_{u'}
\end{aligned}
$$

$\tan\beta = 50$, $\Lambda_{QCD} = 200$ MeV.

$\tan\beta'$	$v'_{\rm wk}$ (TeV)	Λ'_{QCD}(GeV)	$m_{u'}$(GeV)	$m_{d'}$(GeV)	$m_{e'}$(GeV)	$m_{p'}$(GeV)	$m_{n'}$(GeV)
50	123	1.06	1.25	2.5	0.25	5.0	6.25
100	164	1.04	1.67	1.67	0.17	5.0	5.0
200	246	1.06	2.5	1.25	0.13	6.25	5.0
500	369	1.27	3.57	0.71	0.07	7.85	5.0

Neutrino masses

- Neutrino Mass matrix:

$$\mathcal{M} = \begin{pmatrix} \mu & M_D & 0 \\ M_D^T & M_R & M_D'^T \\ 0 & M_D' & \mu' \end{pmatrix}$$

- Taking the scenario in which the SM triplet Higgs has no VEV, (free of the EW radiative correction constraints), $\mu = 0$.
- choose $\mu' M_R \ll M_D'^2$: light neutrino mass from Inverse seesaw:

$$M_\nu \approx M_D M_D'^{-1} \mu' M_D'^{T-1} M_D^T = \mu' (v_{\rm wk}/v'_{wk})^2$$

- Type-I seesaw for mirror neutrino mass: $M'_\nu \approx -M'_D M_R^{-1} M_D'^T$
- A mixing between the SM and mirror neutrinos: $U_{\nu\nu'} \sim M_D/M'_D$;

For illustration, choose the following parameters:

$$M_R \approx 1 \times 10^8 \mathrm{GeV},\ y_\nu = 0.015,\ v'_{\mathrm{wk}}/v_{\mathrm{wk}} = 10^3,\ \mu' \approx 100 \mathrm{KeV}\ .$$

- $M_\nu \approx 0.1$ eV, $M'_\nu \approx 150$ MeV
- $U_{\nu\nu'} \sim 10^{-3}$, the mirror neutrinos decay to $e^+e^-\nu$ with lifetime < 0.5 sec.
- For leptogenesis, $K = M_D M_R^{-1} M_D^T / m_* \approx 1.3 \times 10^5$, which implies a small washout factor $\kappa \approx 1 \times 10^{-6}$.
- A primordial CP asymmetry $\epsilon \sim 0.05$ is needed, which can be realized with Resonant leptogenesis.

Constraints of dark matter self interaction

upper bounds on self interaction cross section

- Bullet cluster: $\sigma_{\chi\chi} < 10^{-23}$ cm^2 for 5 GeV dark matter. (S. Randall, 0704.0261)
- Halo shape (ellipticity) $\Gamma^{-1} = (n\sigma_{\chi\chi}v)^{-1} > 10^{10}$ year. DM halo of NGC 720: $n \sim 4$ GeV/cm^3 (Feng, Haibo Yu 0911.0422)
- In this model, $\sigma_{n'n'} \lesssim 10^{-26}$ cm^2, which is safe from the constraints.

BBN constraints

- At the temperature $T_{BBN} \sim 1$ MeV, there is constraints on the light degrees: $g_*(SM) = 10.75$, Extra light d.o.f is constrained by $\Delta N_\nu \leq 1.44$.
- Due to the breaking of $U(1)'_Q$ and the kinetic mixing of the U(1) gauge bosons, the mirror electrons and photons can decay to SM particles: $\gamma' \to e^+e^-$, $e' \to \gamma'\nu$
- The constraints can easily be avoided. *f.g.*

$$\tau_{\gamma'} \approx \left(\frac{50\text{MeV}}{m_{\gamma'}}\right)\left(\frac{7\times10^{-11}}{\varepsilon_\gamma}\right)^2 \text{sec} \ .$$

The strongest constraints for ϵ_γ comes from muon $(g-2)$: $\epsilon_\gamma^2 < 2\times10^{-5}(m_{\gamma'}/100\text{MeV})^2$.

- The massive mirror photon portal also makes the direct detection of the mirror asymmetric dark matter possible.

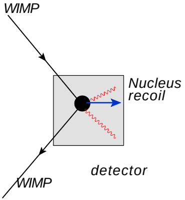
‘Origin Unified’: an uncompleted list

- arXiv:1008.1997 “Darkogenesis”, by J. Shelton and K. Zurek;
- arXiv:1008.2399 “Hylogenesis”, by H. Davoudiasl D. Morrissey, K. Sigurdson and S. Tulin;
- arXiv:1009.0270 “Xogenesis”, by M. Buckley and L. Randall;
- arXiv:1009.2690 “WIMP DM and Baryogenesis”, Gu, Linder, Sarkar and Zhang;
- arXiv:1009.3159 “Aidnogenesis”, M. Blennow, B. Dasgupta, E. Fernandez-Martinez, N. Rius;
- arXiv:1010.0245 “A unified theory of Matter genesis”, L. Hall, J. March-Russell and S. West;
- arXiv:1011.1286 “Cladogenesis”, by R. Allahverdi, B. Dutta and K. Sinha;
- ...

Direct detection of dark matter

- Direct detection of halo particles in terrestrial detectors; (XENON10/100, CDMS, DAMA, CoGeNT, CRESST,...)
- Elastic scattering producing a nucleus recoil. (phonons (heat), ionization, scintillation)

$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2 (1-\cos\theta)}{m_N} \lesssim (1\text{–}50)\mathrm{KeV}$$



- Interaction rate: $R = n_\chi v_\chi N_T \sigma$.
- Rate spectral:

$$\frac{dR}{dE_r} = N_T \frac{\rho_0}{m_\chi} \int_{v_{\min}}^{v_{\max}} \frac{d\sigma}{dE_r} v f(v, v_e) d^3\mathbf{v}\,,$$

$$v_{\min} = \sqrt{m_A E_r/(2\mu^2)}$$

- Spin independent (SI) and spin dependent (SD) interaction:

$$\frac{d\sigma}{dE_r} = \frac{m_A}{2\mu^2 v^2}(\sigma^0_{\rm SI} F^2(|\mathbf{q}|) + \sigma^0_{\rm SD} S(|\mathbf{q}|)/S(0))$$

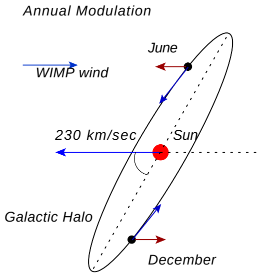
  F, S are form factors.

- standard Maxwellian velocity distribution:

$$f(\mathbf{u}) = f(\mathbf{v}+\mathbf{v}_e) = \frac{1}{(\pi v_0^2)^{3/2}} e^{-\mathbf{u}^2/v_0^2}$$

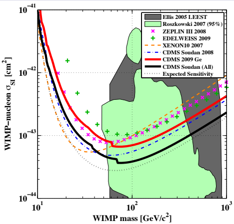
- Annual modulation:

  Earth rotates with respect to Sun
  $v_e = v_\odot + 14.4\cos[2\pi(t-t_0)/T]$.

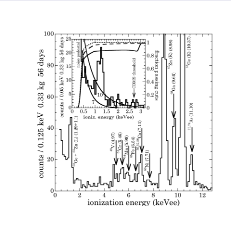


Experiments survey

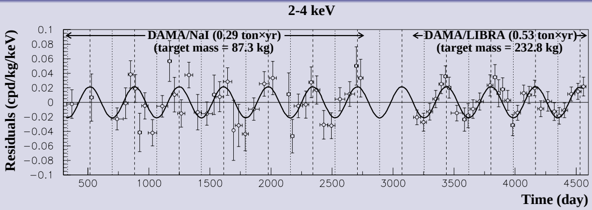
Null Experiments: CDMS (Ge, Si), XENON10 (Xe)



CoGeNT (Ge)



DAMA (NaI)



Direct detection through a massive U(1) portal

- Interactions:

$$\begin{aligned}\mathcal{L} &= \varepsilon_\gamma e\bar{p}\gamma^\mu p A'_\mu + \varepsilon_\gamma \frac{\mu_N}{2}\bar{N}\sigma^{\mu\nu}NF'_{\mu\nu} \\ \mathcal{L}' &= c_1\frac{e}{2m_\chi}\bar{\chi}\sigma^{\mu\nu}\chi F'_{\mu\nu} + c_2\frac{e}{2m_\chi^2}\bar{\chi}\gamma^\mu\chi\partial^\nu F'_{\mu\nu} + \ldots\end{aligned}$$

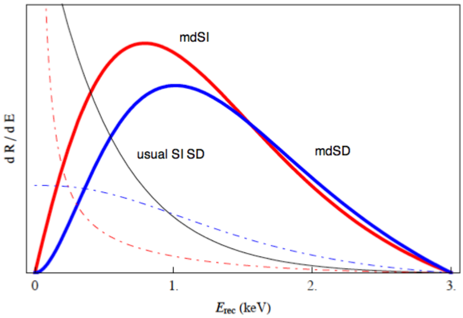
c_1 and c_2 are related to the physical quantities of the magnetic dipole moment and the generalized "charge radius".

- SI and SD interaction matrix elements (NR limits)

$$\begin{aligned}& \varepsilon_\gamma\frac{(c_1+c_2)e^2}{2m_\chi^2 m_{\gamma'}^2}|\mathbf{q}|^2(p_h^\dagger p_h)(\chi_h^\dagger\chi_h) \\ + \quad & \varepsilon_\gamma\frac{c_1 e^2}{2\mu m_\chi m_{\gamma'}^2}(\mathbf{q}\times\mathbf{P})^i(p_h^\dagger p_h)(\chi_h^\dagger\sigma^i\chi_h) \\ + \quad & \varepsilon_\gamma\frac{(\frac{e}{2m_p}+\mu_p)c_1 e}{m_\chi m_{\gamma'}^2}(|\mathbf{q}|^2\delta_{ij}-q^iq^j)(p_h^\dagger\sigma^i p_h)(\chi^\dagger\sigma^j\chi_h) \\ + \quad & \varepsilon_\gamma\frac{\mu_n c_1 e}{m_\chi m_{\gamma'}^2}(|\mathbf{q}|^2\delta_{ij}-q^iq^j)(n_h^\dagger\sigma^i n_h)(\chi^\dagger\sigma^j\chi_h)\ .\end{aligned}$$

Momentum dependent cross section

Unlike the usual dark matter SI and SD interaction, the cross sections have strong momentum dependence. The rate has different spectral.

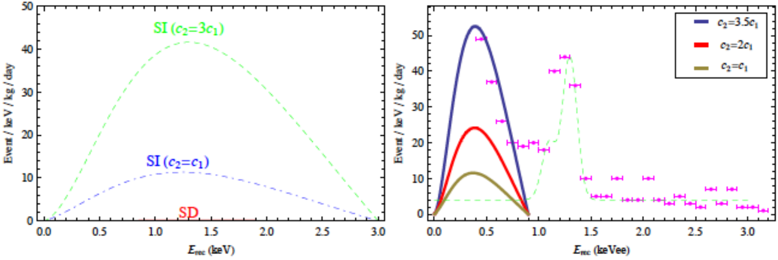


dashed line: massless mirror photon

CoGeNT

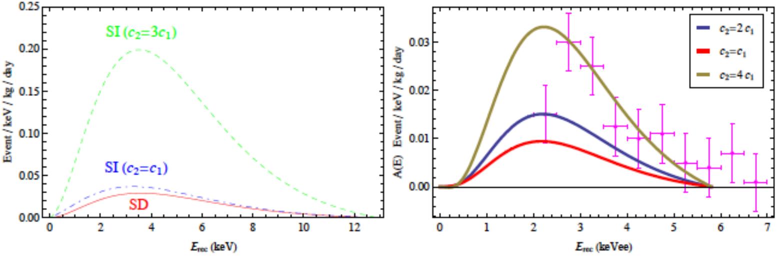
Calculate c1 in the naive quark model picture, take c2 as a free parameter.

take $m_{\gamma'} = 10\,\text{MeV}$ and $\epsilon_\gamma^2 = 2 \times 10^{-7}$ and a quenching factor $Q = 0.3$.



DAMA

For DAMA, we choose $m_{\gamma'} = 10\,\text{MeV}$ and $\epsilon_\gamma^2 = 0.5 \times 10^{-7}$ and $Q = 0.45$.



Summary

1. Origins for Matter and Dark matter are unified. A common set of Neutrino singlets are shared by SM and hidden sector. The mass of dark matter is predicted about 5 GeV.
2. The U(1)-U(1)' kinetic mixing along with a massive dark photon helps us to maintain consistency of the model with BBN. The dark photon also provides a portal linking the two sectors and makes the direct detection of the dark matter possible.
3. The direct detection of the dark baryon is investigated. Different from usual dark matter, the interaction has strong momentum dependent. The differential rate has very different spectral.